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Investigating RaDAR–LiDAR synergy in a North Carolina pine forest

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Abstract

A low frequency (80–120 MHz) VHF RaDAR, BioSAR, specifically designed for forest biomass estimation and a profiling LiDAR, PALS, were flown over loblolly pine plantations in the southeastern United States. LiDAR-only, RaDAR-only, and joint LiDAR–RaDAR linear models were developed to determine if returns from two sensors could be used to estimate pine biomass more accurately and precisely than returns from either sensor alone. The best five-variable RaDAR model explained 81.8% (R^2) of the stem green biomass variability, with a regression RMSE of 57.5 t/ha. The best one-variable LiDAR model explained 93.3% of the biomass variation (RMSE = 33.9 t/ha). Combining the RaDAR normalized volumetric returns with the profiling LiDAR ranging measurements did little to improve the best LiDAR-only model. The best LiDAR–RaDAR model explained 93.8% of the biomass variation (RSME = 32.7 t/ha). Cross-validation and training/test validation procedures demonstrated (1) that all models are unbiased and (2) the increased precision of the LiDAR-only and LiDAR–RaDAR models. The results of this investigation and a companion study indicate that there is little to be gained combining VHF–RaDAR volumetric returns and profiling LiDAR ranging measurements in pine forests; a LiDAR ranging system is sufficient for accurate, precise biomass estimation.

Keywords: VHF RaDAR; Profiling LiDAR; Biomass; RaDAR–LiDAR synergy

1. Introduction

Numerous investigators in the airborne RaDAR and LiDAR remote sensing field have indicated that both portions of the electromagnetic spectrum (EMS) can be used to estimate aboveground forest volume and biomass. RaDAR sensors employed in more recent forestry-related studies have typically recorded volumetric, low-frequency VHF returns or higher frequency UHF measurements. Low frequency systems emit pulsed radio waves in the 20 to 120 MHz range, e.g., CARABAS (20–90 MHz, Fransson et al., 2000), BioSAR (80–120 MHz, Imhoff et al., 2001). UHF signals in the 250 MHz (P-band) to 9800 MHz (X-band) range, in conjunction with interferometric SAR techniques, are used to measure range to the forest canopy and to ground, e.g., GeoSAR (Hensley et al., 2001), AirSAR (Lucas et al., 2006). Vegetation LiDARs, due to the physics of laser construction and the reflectivity of vegetation, typically work in the visible green and near-infrared portions of the EMS to measure forest canopy height and crown closure.

Early work with RaDAR sensors indicated that UHF volumetric returns tended to saturate at forest biomass levels exceeding 200 t/ha (Dobson et al., 1992; Imhoff, 1995). Dobson et al. (1992) reported a P-band (440 MHz, $\lambda = 0.7$ m) biomass saturation limit of 200 t/ha and an L-band (1250 MHz, $\lambda = 0.24$ m) limit of 100 t/ha. Imhoff (1995) reported a saturation limit of 100 t/ha for P-band radars, 40 t/ha for L-band radars, and 20 t/ha for C-band radars (5300 MHz, $\lambda = 0.05$ m). Imhoff concluded that use of such space-based UHF systems would exclude 38% of the Earth's vegetated surface containing 81% of the terrestrial biomass from an accurate global biomass assessment. Asymptotic limits similar to those reported by Imhoff are noted in Lucas et al. (2006), their Figs. 7 and 8.

Subsequent studies have found that lower frequency, longer wavelength RaDARs in the VHF range (20 to 120 MHz, $\lambda = 15.0$ m to 2.5 m, respectively) do not run up against this phytomass limit and, in fact, biomass discrimination improves as the radio frequency decreases (Imhoff et al., 1998). Magnusson and Fransson (2004a,b) used the CARABAS VHF wide-band RaDAR (20–90 MHz, $\lambda = 15.0$ m to 3.3 m,

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respectively) in conjunction with Landsat TM and SPOT multispectral data to estimate stem volume in southern Sweden. Stem volumes ranged from 15 to 585 m^3/ha. In both studies, they found that the combined optical-RaDAR data sets were best for predicting stand-level volume. Interestingly, they found that the CARABAS data predicted stem volume most accurately in high-volume situations, whereas the optical data were more accurate in low-volume circumstances. Smith et al. (2002), working with the CARABAS VHF system and scanning LiDAR data at the individual tree crown level, concluded that the VHF radar returns provided a more direct measure of tree volume than the LiDAR.

Vegetation measurements can also be obtained using interferometric processing techniques in conjunction with synthetic aperture RaDAR systems, InSAR, in order to gather position information, e.g., range to top-of-canopy (X band) or range to ground (P band). Though discussion of interferometric techniques is beyond the scope of this paper, researchers have demonstrated that biomass saturation limits can be increased by employing interferometry. Papathanassiou and Cloude (2001) used polarized L-band interferometry to measure tree heights on 8 coniferous and 6 deciduous forest stands in Germany. They found that the standard deviation of the difference between ground-measured height and RaDAR estimates was 2.5 m. Santoro et al. (2002) employed multi-baseline, i.e., repeat-pass, C-band SAR interferometry to infer stem volumes up to 200 m^3/ha. Above that, C-band sensitivity to increasing stem volume decreased, though they were able to estimate stem volumes up to 350 m^3/ha. They noted that changes in rainfall, temperature, and wind between overpasses degraded volume retrievals. Treuhaft et al. (2003) fused C-band InSAR and airborne hyperspectral data to estimate biomass on 11 stands in Oregon. The standard deviation of the difference between ground and RaDAR estimates of biomass was 25 t/ha on stands ranging from ~25 t/ha up to ~270 t/ha. Askne et al. (2003) employed space-based C- and L-band, multi-baseline InSAR to retrieve stem volumes on boreal forest stands up to 335 m^3/ha with an RMSE of ~10 m^3/ha for C-band and ~30–35 m^3/ha for L-band. Like Santoro et al. (2002), they note that unstable weather conditions between overpasses exacerbate volume retrievals.

Airborne LiDAR researchers, over the last two decades, have empirically related small-footprint (<1 m spot size) LiDAR ranging measurements of tree heights, height variability, intra-crown canopy densities, and/or crown closure to forest volume (e.g., Holmgren, 2004; Maclean & Krabill, 1986; Maltamo et al., 2006; Næsset, 1997; Nelson et al., 1988; Nilsson, 1996), biomass (e.g., Nelson et al., 1988, 2004), basal area (e.g., Gobakken & Næsset, 2004; Holmgren, 2004), and stem counts (e.g., Maltamo et al., 2004; Næsset & Bjerknes, 2001). For instance, Næsset (2002) used small-footprint scanning LiDAR to predict various plot heights, basal area, and volume of Norway spruce and Scots pine stands in Norway. Log–log volume model R^2 values ranged from 0.80 to 0.93, with nonsignificant difference between ground and LiDAR estimates (RMSE = 18.3 to 31.9 m^3/ha). Holmgren et al. (2003) obtained similar results working in spruce/pine stands in Sweden. Means et al. (2000), working in the northwestern U.S., reported a linear volume model with an R^2 = 0.95 and an RMSE of 73 m^3/ha in stands ranging up to 2500 m^3/ha. Nelson et al. (1988) used a profiling LiDAR in conjunction with linear models to estimate pine biomass in southwestern Georgia, USA — R^2 ~ 0.5, RMSEs ~70 t/ha. No LiDAR research known to the current study's authors have noted any saturation effect or asymptotic limit to volume or biomass estimation. LiDAR forestry has matured to the point where small-footprint airborne scanning LiDAR is routinely used in Norway and Sweden for forest structural measurement and management planning (Næsset, 2004; Næsset et al., 2004; T. Aasland 2006, personal communication).

Recent North American studies have demonstrated that (1) forest volume or biomass can be estimated across extensive regions using generic, airborne LiDAR-based equations and (2) low density scanning LiDAR data sets (post spacings>>1 m apart) can be used to acquire those regional measurements. Lefsky et al. (2005b) reported robust biomass and LAI equations applicable across five diverse sites in the Pacific Northwest. Rooker Jensen et al. (2006) demonstrated that regression models relating ground-measured height, basal area, and wood volume to LiDAR heights could be generalized across structurally and topographically variable coniferous sites in Idaho. Thomas et al. (2006) compared low density (5 m post spacing) and high density (0.5 m) LiDAR datasets. While concerns were expressed about the use of low density LiDAR for regional estimation, no degradation in predictive capacity was found.

Both technologies have demonstrated a capacity to sense forest structure which scientists exploit to estimate the amount of aboveground wood. But can RaDAR and LiDAR measurements, considered jointly, be used to predict forest biomass better than either separately? Previous studies comparing and/or jointly considering RaDAR and LiDAR data sets are somewhat sparse, though interest in sensor synergy is increasing. Slatton et al. (2001) used systematically sampled strips of scanning LiDAR measurements as ground reference data to calibrate ground and vegetation height measurements made by a interferometric SAR. Slatton et al.'s Figs. 13–15 directly compare C-band InSAR and LiDAR vegetation height measurements. Lucas et al. (2005) did not directly compare LiDAR and SAR data sets, but they did employ the LiDAR measurements to help understand AirSAR C, L, and P band returns. They employed field data, scanning LiDAR data, aerial photography, and CASI (Compact Airborne Spectrographic Imager) multispectral observations to create 3-D forest canopies in order to develop an AirSAR simulation model. Breidenbach et al. (2006) compared scanning LiDAR and InSAR ranging measurements to see which best estimated tree heights on 250 poly-areal forest inventory plots in beech-spruce-oak forests near Stuttgart, Germany. In this study, the LiDAR last-pulse ground returns were used to create a digital terrain model (DTM). The LiDAR first returns and the InSAR X-band top-of-canopy returns were combined with the LiDAR DTM to see which data source best-predicted tree heights. The RMSE of the plot-level InSAR height estimates was 2.69 m (CV = 9.5%), whereas the comparable LiDAR RMSE was 1.85 m (CV = 6.6%). The authors concluded that "The use of laser scanner data is more appropriate when a high level of accuracy for the estimation of tree height or vegetation height structure is required." As noted above (Askne et al., 2003; Santoro et al., 2002), multi-baseline interferometry may improve performance of the X-band height estimates.